Tray Columns: Design

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Distillation has remained an important separation technology for the chemical process industries. In 1997 it was reported in the journal *Chemical Engineering* that about 95% of all worldwide separation processes use this technology. In the USA alone, some 40 000 distillation columns represent a capital investment of about US $8 billion. They consume the energy equivalent of approximately 1 billion barrels of crude oil per day. Such columns are used in refineries, petrochemical plants, gas processing plants and organic chemical plants to purify natural gas, improve gasoline, produce petrochemicals and organic products, recover pollulant species, etc.

Distillation can be carried out in a tray or a packed column. The major considerations involved in the choice of the column type are operating pressure and design reliability. As pressure increases, tray coulmns become more efficient for mass transfer and can often tolerate the pressure drop across the trays. The design procedure for the large diameter tray column is also more reliable than that for the packed column. Thus, trays are usually selected for large pressurized column applications.

Distillation trays can be classified as:

1. cross-flow trays with downcomers (see **Figure 1**A);
2. countercurrent trays without downcomers (also known as dual-flow trays) (see Figure 1B).

The-dual flow tray allows the gas and liquid to pass through the same tray openings. This results in a limited operating range because the dispersion height is very sensitive to the gas/liquid flow rates. In general, dual-flow trays are employed only in cases where high capacity or high resistance to fouling are required. However, because of its narrow operating range, the market share is small and such trays will not be discussed further.

The cross-flow tray utilizes a weir on the downcomer to control the spray height on the tray, and thus provides a stable gas–liquid dispersion over a wide range of gas/liquid flows. A tray is the combination of a tray deck, where froth is generated to provide vapour–liquid contact, and a downcomer, where the vapour–liquid mixture is separated. The bulk of the vapour rises from the aerated liquid through the vapour disengagement space to the tray above. However, the passage of the liquid from the top to the bottom of the column occurs mainly via downcomers.

There are three types of cross-flow trays: (1) sieve, (2) valve and (3) bubble cap. Among them, sieve trays offer high capacity and efficiency, low pressure drop, ease of cleaning, and low capital cost, but smaller turndown ratio. Although the design procedure is similar for all three types of trays, only sieve tray performance data are readily available in the public domain. The valve and bubble cap designs are often protected by patents, and thus the performance data are supplied by the vendors. This article describes the procedure for designing an optimum sieve tray. A similar procedure can be applied in principle to the valve and bubble cap trays, provided critical performance data are available.

The cost of a tray column is determined by two factors:

1. column diameter, which determines the throughput;

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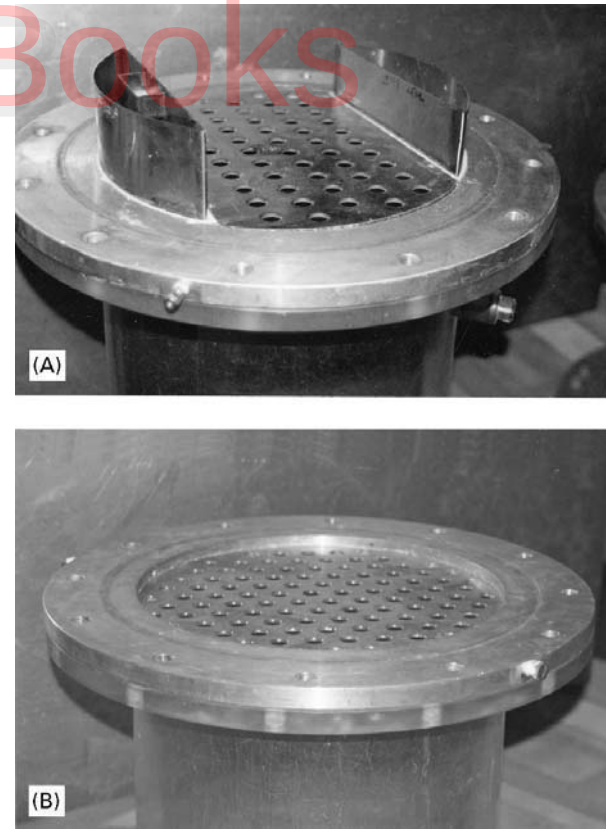

Figure 1 (A) Sieve ray with downcomer in a 30 cm diameter column. (B) Dual-flow tray in a 30 cm diameter column.

2. column height, which delivers the number of equilibrium stages required for the separation.

The minimum cost is generally achieved when the column volume is minimized. The final selection of the tray design is based on the combined cost of the column shell, internals and installation.

It should be noted that the fraction of the cross-sectional area available for vapour–liquid disengagement decreases when the downcomer area is increased. Thus, optimum design of the tray involves a balance between the tray area and the downcomer area (i.e. the capacity for the tray deck should match the capacity of the downcomer). The correlations for sizing trays are implicit in column diameter, tray spacing and tray geometry, thus requiring trial-and-error calculations to arrive at the final selection.

Characteristics of Tray Operation

Typical tray layout is shown in **Figure 2**, and tray operation is shown in **Figure 3**. High speed photography of a large operating tray indicates that the vapour erupts through the liquid sporadically. The holes that are not erupting do not weep appreciably at a vapour rate above the weep point, although the supporting of the liquid by the vapour is not absolutely complete. The interaction of vapour and liquid on a properly designed tray results in a highly turbulent two-phase mixture of a high specific interfacial area with net liquid movement in a crossflow direction to the rising vapour stream. The aerated liquid may be either liquid-continuous (froth) at relatively low vapour velocities or vapour-continuous (spray) at high vapour velocities.

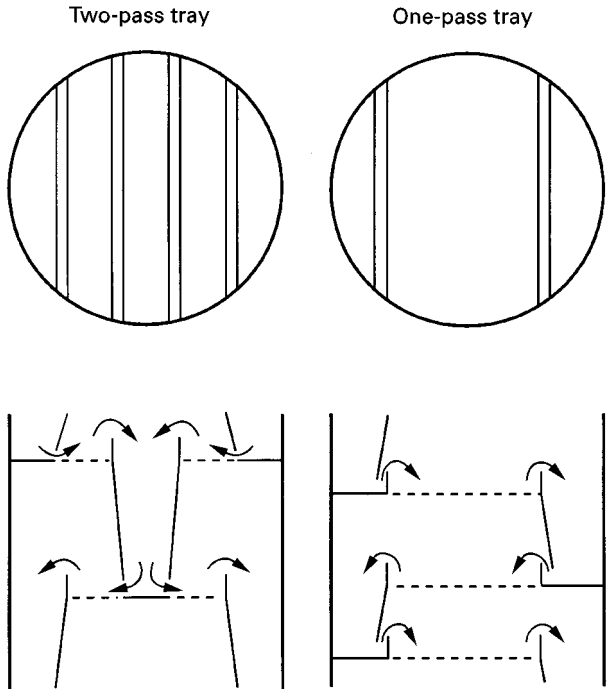

Figure 2 Tray layouts.

The maximum capacity of a sieve tray is reached when the tray is flooded. This may be due to excessive spraying (entrainment) taking place in the intertray space or the froth in the downcomer backing-up to reach the top of the outlet weir. The onset of flooding is accompanied by a sharp increase in tray pressure and a sharp decrease in tray efficiency.

As vapour rates decrease to the point that the vapour flow cannot totally support the liquid on the tray, some liquid will weep through the holes. If the weepage is so severe that no liquid flows over the outlet weir, the tray cannot operate stably under these dumping conditions. The minimum capacity of the tray is normally reached when moderate weepage is encountered. Ideally, a sieve tray should operate in the shaded area shown in **Figure 4** to ensure proper operation.

Tray efficiency can be divided into two components:

1. point efficiency as determined by the vertical flow of vapour through the froth;
2. tray efficiency enhancement by the crossflow of liquid.

The physical properties of the vapour–liquid mixture determine the point efficiency, although froth height, which influences the gas residence time, also has a significant effect, especially for low efficiency systems. Liquid flow pathlength determines the liquid residence time and the extent of crossflow tray efficiency enhancement. Entrainment and weeping depress tray efficiency by disrupting the concentration profile in the column. The froth height and the liquid flow path are two parameters that are optimized to give maximum tray efficiency. Other geometric variables, such as open hole area, hole diameter and downcomer arrangement, also affect tray hydraulics and efficiency. The goal for a tray design is to reach maximum tray efficiency without compromising hydraulic stability.

The steps required for tray column design are shown in **Figure 5**; a detailed discussion of each step is given below.

Input Data

Once sieve trays are selected for a given application, the input data that are required in the design calculations include density, viscosity, surface tension, diffusivity and flow rate of the liquid stream, as

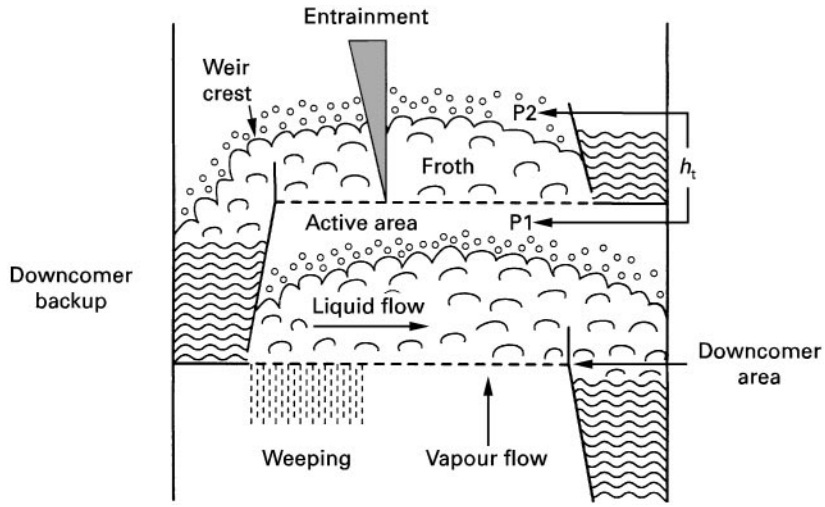

Figure 3 Tray operation schematic diagram.

well as density, diffusivity and flow rate of the vapour stream. This information can be obtained by performing tray-to-tray distillation calculations; several commercial computer packages are available for this purpose (e.g. PRO II, ASPEN PLUS, HYSIM).

As the physical properties and the vapour and liquid flow rates vary throughout a given column, it is difficult to provide a single design for the entire column. Instead, the column is divided into a number of sections. Within each section, trays are designed with the same layout. Normally the section is a set of trays bounded by two column penetrations (feed and/or drawoff). Tray design calculations should be performed to ensure that trays at the top and bottom of the section meet the design requirements.

Preliminary Specifications

Tray Spacing

Tray spacing is set by maintenance requirements, and also by support structure design in large-diameter columns. Sufficient crawl space must be provided for tray cleaning and repair. From these considerations, the minimum tray spacing is about 12 in (30 cm) for column diameter less than 5 ft, and (150cm) and 18 in (45 cm) for a column diameter greater than 10 ft (300 cm). In general, it is best to keep tray spacing to a minimum, which is often the most economical.

Downcomer Area

The downcomer area at the top is sized such that the velocity of the ascending vapour bubbles exceeds the downflow velocity of the liquid. The size is related to the stability of the froth in the downcomer and determined by the residence time required for achieving the separation of the two-phase mixture. For non-foaming systems, such as lower alcohols, a residence time of 3 s is sufficient, whereas for extremely high foaming systems such as caustic regenerators, 9 s is required.

To prevent the liquid coming off the bubbling area from splashing against the column wall, the minimum downcomer width is 5 in (12.7 cm). Also, the minimum side chord length should be 60% of the column diameter. This is required to maintain good liquid distribution on the tray.

Since the separation of the vapour–liquid mixture is complete at the bottom of the downcomer, a sloped downcomer can be used to maximize the active tray area. In this case, the downcomer area at the bottom should be about 60% of that at the top.

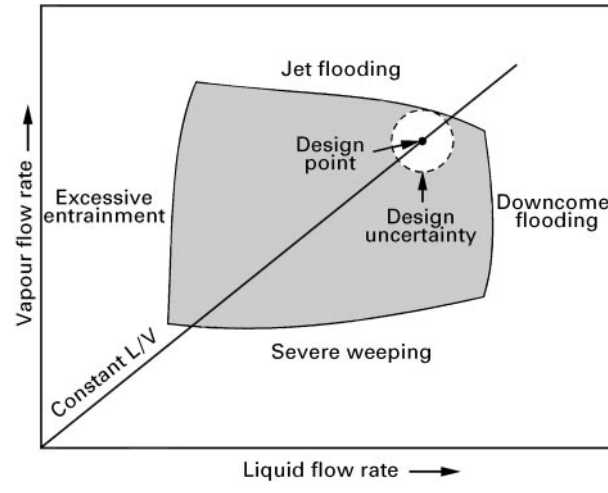

Figure 4 Sieve tray performance diagram.

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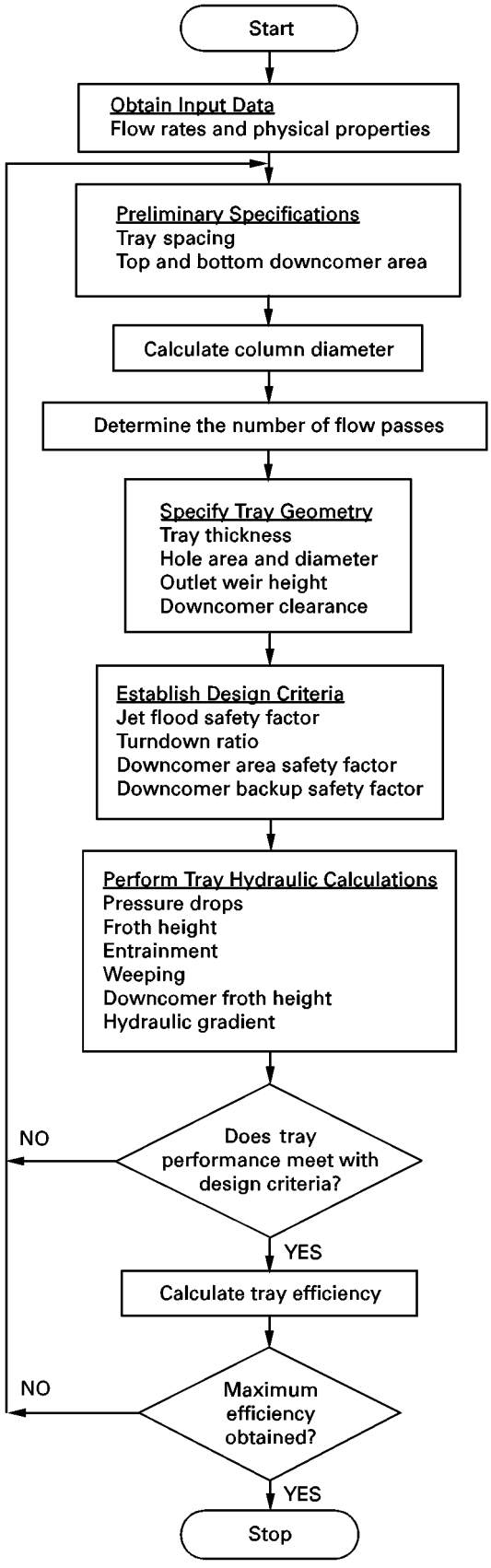

Figure 5 Sieve tray design procedure.

It should be noted that the downcomer area occupies only a small fraction of the cross-sectional area. Thus, a small overdesign does not result in a significant economic penalty.

Column Diameter

The column diameter can be calculated once the tray spacing and downcomer area have been specified. The Fair correlation, based on the Souders and Brown criterion, is recommended by most designers. The vapour flooding velocity can be calculated from eqn [1].

$$U_{N,f} = C_{SB}\left(\frac{\rho_L - \rho_V}{\rho_V}\right)^{0.5}\left(\frac{\sigma_L}{20}\right)^{0.2} \qquad [1]$$

In eqn [1] C_{SB} is the Souders–Brown coefficient, ρ_L and σ_L (dyne cm^{-1}) are liquid density and surface tension, respectively, and ρ_V is the vapour density in the same units as ρ_L. $U_{N,f}$ is based on the net area, A_N(ft^2), which is the active area plus one downcomer area. The unit for $U_{N,f}$ is ft s^{-1}. The most popular empirical formula for calculating C_{SB} is given in eqn [2].

$$\begin{aligned} C_{SB}(\text{ft s}^{-1}) = {} & 0.04232 + 0.1674T_S \\ & + (0.0063 - 0.2686T_S)F_{lv} \\ & + (0.1448T_S - 0.008)F_{lv}^2 \end{aligned} \qquad [2]$$

In this equation $F_{lv} = (L/V)(\rho_V/\rho_L)^{0.5}$, T_S is tray spacing in feet, and L and V are mass flow rates of the liquid and vapour. The C_{SB} is valid for trays with a fractional hole area greater than 10%. For areas of 8% and 6%, C_{SB} should be multiplied by 0.9 and 0.8, respectively.

Knowing $U_{N,f}$ and the total vapour flow rate, the column diameter can be calculated by assuming that the column will be operated at a lower vapour velocity, say 80% of the flood point.

Number of Flow Passes

The number of flow passes is set to allow the tray to operate at a weir loading that does not result in excessive weir crest. The weir loading can be calculated once the column diameter and the downcomer area are determined. The optimum weir loading is 4–6 US gallons per minute and the maximum loading is about 20. Downcomer choking, which causes liquid build-up on the tray, may occur if the maximum value is exceeded. Increasing the number of flow passes provides a solution to this problem (see Figure 2). However, shorter liquid flow path and possible maldistribution of liquid and vapour streams in multipass trays may result in lower tray efficiency.

As a rule of thumb, the liquid and vapour handling capacity are a direct function of weir loading and column area, respectively. Since weir length and column area are proportional to column diameter and diameter squared, respectively, the use of multipass trays is often necessary for large-diameter columns.

Tray Geometry

Tray geometry should be chosen so that hydraulic and efficiency calculations can be performed to arrive at the optimum design. The following parameters must be specified for tray design calculations.

Tray Thickness

The choice of material for the fabrication of trays is dependent mainly on the corrosion properties of the process fluids. In general, tray thickness is about gauge 10 (0.134 in; 3.40 mm) for carbon steel and gauge 12 (0.109 in; 2.77 mm) for stainless steel. For economic reasons the holes are punched, which dictates that the thickness must be less than the hole diameter.

Hole Diameter

Small holes with a diameter in the range of $\frac{3}{16}$ to $\frac{1}{4}$ in (4.76–6.35 mm) give better hydraulic and mass transfer performance than the large ones in the range of $\frac{1}{2}$ to $\frac{3}{4}$ in (12.7–19.0 mm). However, large-hole trays are cheaper and show more resistance to fouling. Choose the hole size according to design requirements.

Hole Area

The hole area is normally in the range of 5–16% of the bubbling area. Lower hole area allows the tray to operate at higher efficiency and turndown ratio, but at the expense of higher pressure drop. Since the operating pressure of the column dictates the maximum allowable pressure drop, the hole area is selected according to the type of service. Recommended values are 5–10% for pressure and 10–16% for vacuum operations.

Hole areas below 5% are not used because the distance between holes becomes excessive and liquid channelling may occur. However, the distance can also be adjusted by changing the hole diameter. In general, the hole pitch should not be larger than 2.5 in (6.35 cm). On the other hand, if the hole areas are greater than 16%, significant weeping and entrainment may coexist and the design equations may not apply under these conditions.

Weir Design

Outlet weirs are used to control the froth height on the tray. For most trays, the outlet weir height is about 1–4 in (2.5–10 cm) and the downcomer clearance, where the liquid is discharged from the bottom of the downcomer onto the tray below, should be 0.5 in (1.25 cm) smaller than the outlet weir height to ensure a positive downcomer seal.

From the above discussion, it may be concluded that the object of tray design is to obtain the optimum combination of the following parameters:

1. column diameter
2. tray spacing
3. top and bottom downcomer area
4. hole diameter and hole area
5. outlet weir height and downcomer clearance.

Design Criteria

The trays should be designed for maximum throughput. However, owing to inaccuracies in the design equations and fluctuation of process conditions (e.g. flow rates, temperature and pressure), safety factors are needed to ensure stable column operation at all times (see Figure 4).

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Jet Flood Safety Factor

The jet flood safety factor (JFSF) is defined as the ratio of vapour velocity required to entrain the entire liquid flow (U_{max}) to the operating velocity (U_{op}). It is a useful measure of entrainment and hydraulic stability. The typical JFSF value is 1.2.

Turndown Ratio

For various reasons, the column may be operated at a reduced throughput. Weeping is encountered if the vapour velocity can no longer support the liquid on the tray. Although flow dynamics permit stable operation as long as dumping is avoided, tray efficiency suffers because weeping reduces the vapour–liquid contact. The turndown ratio is the ratio of the design vapour flow rate to the flow rate that permits some weeping without seriously affecting the tray efficiency. Recommended weepages at turndown conditions for vacuum and pressure operations are 3% and 7%, respectively.

Downcomer Area Safety Factor (DCASF) and Downcomer Backup Safety Factor (DCBUSF)

The liquid handling capacity of a tray is determined by downcomer design and tray spacing. The DCASF determines the approach of the top downcomer area

to the minimum area to the minimum area required for vapour–liquid disengagement. The DCBUSF determines the approach of the downcomer froth height to the downcomer depth (= tray spacing + outlet weir height). Safety factors in the range of 1.5–2.0 are recommended.

Pressure Drop

The pressure drop across an operating tray should be specified if it affects the number of equilibrium stage requirements for the separation. This is often the case for vacuum applications. Stable operation can be obtained at a pressure drop of 1–3 in (2.5–7.6 cm) of liquid per tray for vacuum and 2–5 in (5.1–12.7 cm) for pressure operations.

Design Calculations

Tray Hydraulics

The hydraulic performance of a sieve tray for a given layout may be calculated using the methods presented in 'Distillation/Tray Columns: Performance'.

Tray Efficiency

Tray efficiency is a strong function of the physical properties of the vapour and liquid streams. It is also affected, to a lesser extent, by the flow rates and tray layout. In the latter case, only hole diameter, hole area and weir height have a small influence on the tray efficiency. The optimum design, which gives the maximum number of equilibrium stages in a column, is often obtained at minimum tray spacing and minimum number of flow paths that satisfy the hydraulic design criteria.

Conclusions

A well-designed tray should be economical while meeting all process design requirements. Economic considerations suggest that it is best to use the smallest column diameter and height that satisfy the process requirements within reasonable safety allowances. Process requirements include accommodation of the expected liquid and vapour flow ranges and the optimization of tray efficiency.

See also: **II/Distillation:** Packed Columns: Design and Performance; Theory of Distillation; Tray Columns: Performance.

Further Reading

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Tray Columns: Performance

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Introduction

As pointed out in the article entitled distillation tray columns: design, a sieve tray is designed with a number of objectives in mind. They include: (i) achieving high efficiency of contact between the liquid and the vapour so that the phases leaving a tray are as close to equilibrium conditions as possible; (ii) balancing the tray deck area provided for vapour/liquid contact with the downcomer area provided for disengagement of the two phases so that neither limits the capacity of the column to process large amounts of feed; and (iii) avoiding detrimental operating